Using the Higgs boson to probe the littlest Higgs model with T-parity through $Z_H W_H$ production at the LHC

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Abstract

In the littlest Higgs model with T-parity, the production cross section of the T-odd heavy gauge boson pair $Z_H W_H$ is sizable at the LHC. In addition, both the Z_H and W_H bosons have almost exclusively one decay channel into $H A_H$ and $W A_H$ respectively, where the dark matter candidate A_H yields a large missing transverse energy signal. Upon the discovery of the Higgs boson at 125 GeV, we study the discovery sensitivity of the final state $pp \to \ell b \bar{b} + \not{E}_T$ to probe the model at the LHC. We find that the standard model backgrounds are manageable by applying suitable kinematic cuts. The LHC running at $\sqrt{s} = 14$ TeV with a $100\,\mathrm{fb}^{-1}$ total luminosity is sensitive to the model with the signal significance above 5 if the symmetry breaking scale f is below about 850 GeV.

I. INTRODUCTION

After a long wait, a particle with close resemblance to the standard model (SM) Higgs boson was finally discovered at the Large Hadron Collider (LHC). Based on 2011 and 2012 data at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, the observation of a new boson with mass around 125 GeV was declared by the ATLAS and CMS collaborations with a local significance of 5.0 standard deviation [1–4]. The CDF and D0 collaborations also supported this discovery through the excess in the $H \to b\bar{b}$ channel [5].

The excitement at this great discovery is common in the whole particle physics community. The interpretation of the detailed data splits though. One approach is to take some deviation of the Higgs data from the SM expectation as a signal of new physics [6], especially the enhanced rate in the $\gamma\gamma$ channel with about 2σ [7]. The other approach is to accept the observed new boson as the SM Higgs boson with mass of 125 GeV. The 2σ deviation in the $\gamma\gamma$ mode could fade away with more data.

We take an alternative stance: new physics beyond the SM exists at the TeV scale, and we probe it by using the SM-like dominant decay of the Higgs boson, not by the deviation in the $H \to \gamma\gamma$ channel. The hint of new physics is from the observed mass of the Higgs boson, which demands an answer to the gauge hierarchy problem. Accepting almost the same properties with the *SM* Higgs boson, we can use it as a tagging particle for new physics. This is very useful especially when the Higgs boson is a decay product of a heavy new particle. The final state is a tagged Higgs boson, *e.g.*, through a b quark pair with the invariant mass near 125 GeV, accompanied by additional exotic signals such as large missing transverse energy $\not{E}_T$.

In this direction, the littlest Higgs model with T-parity invariance, called the LHT model [8–10], has drawn a lot of interest as it provides an answer to the gauge hierarchy problem and a candidate for the cold dark matter. The model is based on an $SU(5)/SO(5)$ non-linear sigma model, accommodating the Higgs boson as a pseudo-Nambu-Goldstone boson. Collective symmetry breaking mechanism prohibits one-loop quadratic divergence in the radiative corrections to the mass of the Higgs boson. The little hierarchy problem is postponed to much higher energy $O(10)$ TeV. Phenomenologically, each SM particle has a new heavy partner. In order to weaken the strong constraint from the electroweak precision data [11], T-parity was implemented later [9, 10], under which the new partners of the SM

particles have odd parity while the SM particles have even parity. The lightest new particle A_H, the partner of the SM $U(1)_Y$ gauge boson, becomes stable and weakly-interacting, and thus a good dark matter candidate [12]. Many interesting phenomenological signatures at high energy colliders have been studied in the literature [13–16], including the implication for the LHC Higgs data [17].

The new heavy partner of the SM neutral $SU(2)$ gauge boson, Z_H, is especially interesting since it decays almost exclusively into the SM Higgs boson and the cold dark matter particle A_H. By observing the Higgs boson with large $\not{E}_T$, we have an additional channel to probe the LHT model. The Z_H is mainly produced associated with W_H [14]: the $Z_H Z_H$ production cross section is about an order of magnitude smaller. The W_H boson decays into $W A_H$. If W decays leptonically, the final state of $Z_H W_H$ production is $\ell b \bar{b} + \not{E}_T$, where two A_H's and one neutrino carry $\not{E}_T$. We shall suggest optimal search strategies to enhance the signal significance at the LHC.

The rest of the paper is organized as follows. We begin our discussion with a brief review of the LHT model in Sec. II. In Sec. III, we specify the model parameters for $Z_H W_H$ production, and compute the total production cross sections at the LHC. We also suggest kinematic cuts to suppress the SM backgrounds, and present the signal significance for the LHC energy of $\sqrt{s} = 7$, 8, 14 TeV. We conclude in Sec. IV.

II. BRIEF REVIEW OF THE LHT MODEL

The LHT model is based on an $SU(5)/SO(5)$ non-linear σ-model with a gauge symmetry $[SU(2) \otimes U(1)]^2$. The leading two-derivative term for the sigma field Σ is

$$\mathcal{L}_\Sigma = \frac{1}{2} \frac{f^2}{4} \mathrm{Tr} |\mathcal{D}_\mu \Sigma|^2, \tag{1}$$

where f is the symmetry breaking scale of the order of 1 TeV. The covariant derivative of the sigma field is given by

$$\mathcal{D}_\mu \Sigma = \partial_\mu \Sigma - i \sum_{j=1}^{2} \left\{ g_j W_j^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) + g_j' B_j (Y_j \Sigma + \Sigma Y_j^T) \right\}. \tag{2}$$

Here B_j and W_j^a are $U(1)_j$ and $SU(2)_j$ gauge fields, respectively, and their corresponding couplings are g_j' and g_j. The generators are $Q_1^a = \mathrm{diag}\,(\sigma^a/2, \mathbf{0}_{3\times3})$, $Q_2^a = \mathrm{diag}\,(\mathbf{0}_{3\times3}, -\sigma^{a*}/2)$, $Y_1 = \mathrm{diag}(-3, -3, 2, 2, 2)/10$, and $Y_2 = \mathrm{diag}(-2, -2, -2, 3, 3)/10$.

Symmetry breaking occurs in two stages: (i) the global $SU(5)$ symmetry as well as the $[SU(2) \otimes U(1)]^2$ gauge symmetry are broken by non-zero vacuum expectation value (VEV) of an $SU(5)$ symmetric tensor Σ_0; (ii) the electroweak symmetry is broken as the Higgs field develops non-zero VEV at loop levels. The first stage symmetry breaking is from non-zero Σ_0 field given by

$$\Sigma_0 = \begin{pmatrix} & & \mathbf{1}_{2\times 2} \\ & 1 & \\ \mathbf{1}_{2\times 2} & & \end{pmatrix}. \tag{3}$$

This Σ_0 breaks the global $SU(5)$ symmetry into $SO(5)$ and the gauge symmetry $[SU(2) \otimes U(1)]^2$ into its diagonal subgroup $SU(2)_L \otimes U(1)_Y$. Among 14 massless Goldstone bosons ($\mathbf{1}_0 \oplus \mathbf{3}_0 \oplus \mathbf{2}_{\pm\frac{1}{2}} \oplus \mathbf{3}_{\pm 1}$ representations of the $SU(2)_L$ gauge group) from the global symmetry breaking, $\mathbf{1}_0$ and $\mathbf{3}_0$ are eaten by the broken gauge bosons $\vec{W}_H^\mu$ and $B_H'^\mu$.

The remained Goldstone degrees of freedom, the $SU(2)_L$ doublet h and triplet ϕ, are parameterized by the pion matrix Π. The low energy dynamics of the model is described by the expansion of the sigma field as

$$\Sigma = e^{2i\Pi}\Sigma_0, \tag{4}$$

where the pion field is

$$\Pi = \begin{pmatrix} \phi^\dagger & \frac{h^\dagger}{\sqrt{2}} & \mathbf{0}_{2\times 2} \\ \frac{h^*}{\sqrt{2}} & 0 & \frac{h}{\sqrt{2}} \\ \mathbf{0}_{2\times 2} & \frac{h^T}{\sqrt{2}} & \phi \end{pmatrix}. \tag{5}$$

The second stage of symmetry breaking occurs by the complex doublet $\mathbf{2}_{\pm\frac{1}{2}}$, which has proper quantum numbers for the SM Higgs boson. Its interactions with gauge bosons and fermions generate non-zero VEV as well as its mass at loop level. The quadratic divergence in the radiative Higgs boson mass is avoided by collective symmetry breaking. If one set of $SU(2) \times U(1)$ gauge couplings vanishes, the theory is invariant under a global $SU(3)$ symmetry. The Higgs field remains as an exact Goldstone boson. We need two symmetry breakings for the Higgs radiative mass, which is log-divergent at one-loop level and quadratically divergent at two-loop level. For $\Lambda \sim \mathcal{O}(10)$ TeV, the Higgs boson mass is naturally of the order of 100 GeV.

An inevitable consequence of non-zero VEV of the Higgs field is the tree level mixing between the heavy new particles and the SM particles, which is strongly constrained by

the electroweak precision data [11]. Later T-parity was introduced in order to forbid the tree-level mixing, under which the gauge bosons and pion field are transformed as

$$W_1^a \longleftrightarrow W_2^a, \quad B_1 \longleftrightarrow B_2, \quad \Pi \longleftrightarrow -\Omega\Pi\Omega, \tag{6}$$

where $\Omega = \mathrm{diag}(1,1,-1,1,1)$. If we impose $g_1 = g_2 = \sqrt{2}g$ and $g_1' = g_2' = \sqrt{2}g'$, the Lagrangian in Eq. (2) is T-parity invariant. The heavy gauge bosons are simply $W_H^\pm = (W_1^\pm - W_2^\pm)/\sqrt{2}$, $Z_H = (W_1^3 - W_2^3)/\sqrt{2}$ and $A_H = (B_1 - B_2)/\sqrt{2}$ with the masses of $M_{W_H} = M_{Z_H} = gf$ and $A_H = g'f/\sqrt{5}$ to leading order. New gauge bosons of W_H, Z_H, and A_H have odd T-parity while all the SM fields have even T-parity. There is no tree-level mixing between a SM particle and a new particle.

Another key ingredient in the LHT model is the presence of T-odd fermions, which is crucial for the invariance of T-parity in the model. Their heavy masses are parameterized by Yukawa type coupling κ as $M_{f_-} = \sqrt{2}\kappa f$ [13, 18, 19]. For simplicity, we assume that κ is flavor-diagonal and universal. There are lower and upper bounds on κ. If κ is too small, new fermions become light and are to be copiously produced at the LHC. The pair production of T-odd fermions leaves the final states of jets and missing transverse energy, which is constrained by the search for squarks [20]. If κ is too large, a naive expectation is that all heavy fermions get decoupled from the theory. However four fermion contact interactions have non-decoupling effects from κ. The $e^+e^- \to q\bar{q}$ scattering constrains $\kappa \lesssim 3.4$ [18].

Final comments are on the decay modes of the heavy gauge bosons of Z_H and W_H. Crucial are the two-body ferminonic decays of $Z_H/W_H \to f_- f^{(\prime)}$. For $\kappa \geq 0.46$, however, heavy masses of f_-'s close these decay modes kinematically. The dominant decay mode of Z_H is into HA_H. The next dominant is into HHA_H with the branching ratio of a few percent at most. With $m_H = 125$ GeV, we have $\mathrm{BR}(Z_H \to A_H H) = 99\%$, 97% for $f = 0.5, 1$ TeV respectively. The heavy W_H decays almost exclusively into WA_H.

III. $Z_H W_H$ SIGNAL AT THE LHC

The $Z_H W_H$ production at the LHC is from the $q\bar{q}'$ annihilation. There are three Feynman diagrams: the s-channel one mediated by the SM W boson, the t-channel and u-channel ones by T-odd quarks. An important observation is that the s-channel contribution alone diverges as energy goes to infinity [14]. The t-channel and u-channel contributions interfere
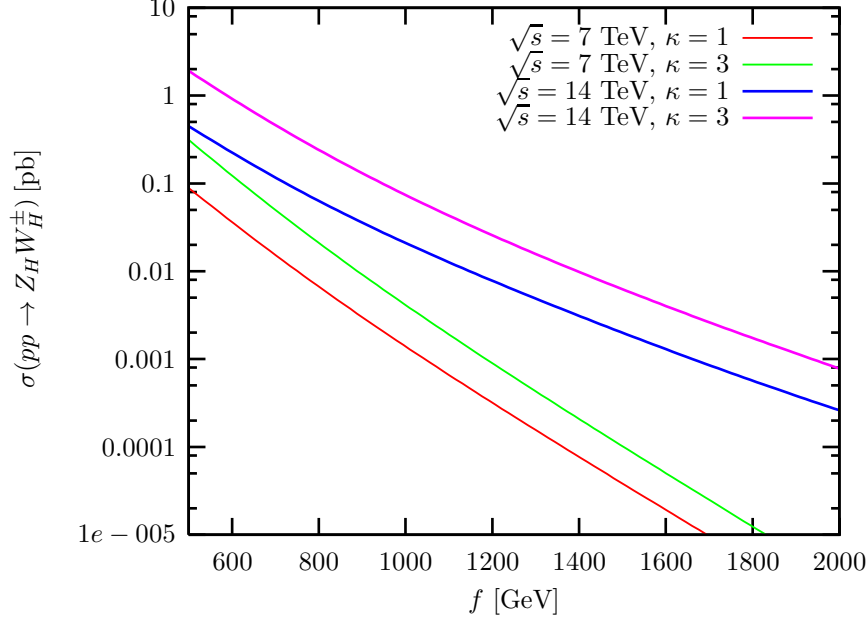
FIG. 1. The total cross section of $Z_H W_H$ at the LHC with $\sqrt{s} = 7, 14$ TeV for $\kappa = 1, 3$ as a function of f.

destructively with the s-channel one, and cancel the diverging contributions. The inclusion of T-odd heavy fermions is crucial in order to respect the partial-wave unitarity.

In Fig. 1, we show the total cross section of $Z_H W_H$ at the LHC with $\sqrt{s} = 7, 14$ TeV for $\kappa = 1, 3$ as a function of f. The result for $\sqrt{s} = 14$ TeV and $\kappa = 1$ is consistent with that in Ref. [14]. If $\kappa = 1$ and $f = 500$ GeV, the total cross section is about 0.45 pb (0.09 pb) for $\sqrt{s} = 14$ (7) TeV. If κ increases into 3, the cross section also increases by a factor of $3 \sim 4$. This is attributed to the weakened destructive interference effects. At the LHC with $\sqrt{s} = 8$ TeV, the total production cross section, compared to $\sqrt{s} = 7$ TeV, increases by $6 - 7\%$. Recently the QCD K-factor at next-to leading order has been calculated to be roughly ~ 1.1 [21].

We consider the dominant subsequent decays of $Z_H W_H$ as in Fig. 2:

$$pp \to Z_H + W_H \to H A_H + W A_H \to b\bar{b} A_H + \ell \nu A_H. \tag{7}$$

Note that both the branching ratios of $\text{BR}(Z_H \to A_H H)$ and $\text{BR}(W_H \to W A_H)$ are almost 100% for $\kappa = 1, 3$. We use MADGRAPH [22] for the signal event generator. The basic cuts

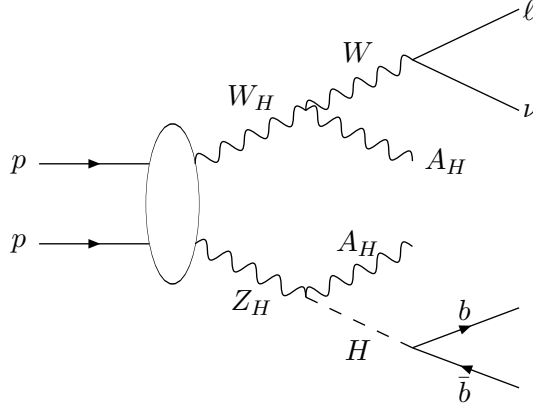FIG. 2. $\ell b\bar{b} + \not{E}_T$ channel from the $Z_H W_H$ decay

on the transverse momentum p_T and the pseudo-rapidity η of jets and charged leptons are

$$p_{Tj} > 50 \text{ GeV}, \quad p_{T\ell} > 25 \text{ GeV}, \quad |\eta_{j,\ell}| < 2.5. \tag{8}$$

The irreducible SM backgrounds are

$$pp \to W + b\bar{b} \to \ell\nu + b\bar{b}, \text{ (QCD)} \tag{9}$$

$$pp \to W + Z \to \ell\nu + b\bar{b}, \tag{10}$$

$$pp \to W + H \to \ell\nu + b\bar{b}. \tag{11}$$

Dominant is the first QCD process in Eq. (9), mediated by the gluon. The cross section of this QCD process with the basic cuts in Eq. (8) is $\sim \mathcal{O}(20)\,\text{pb}$. Our signal with the basic cuts is $\sim \mathcal{O}(1)\,\text{fb}$. Other backgrounds are $pp \to WZ$ and $pp \to WH$. A reducible background comes from $t\bar{t}$ production followed by $t\bar{t}$ decaying into $b\bar{b}\ell\ell\nu\nu$ with one of the charged leptons missed in the detector.

Now we suggest suitable kinematic cuts to suppress the SM backgrounds. First we note that the $b\bar{b}$ in our signal is from the decay of the Higgs boson, while the $b\bar{b}$ in the QCD background is mediated by a gluon. We apply the following cut on the invariant mass of $b\bar{b}$ to suppress the SM backgrounds, especially the QCD one:

$$115 \text{ GeV} < M_{b\bar{b}} < 135 \text{ GeV}. \tag{12}$$

Another sensitive probe is the missing transverse energy. The SM background has $\not{E}_T$ from the neutrino in the W decay, while the $\not{E}_T$ in our signal comes from two heavy A_H's

TABLE I. Signal and background cross sections as well as the signal significance for $pp \to \ell b\bar{b} + \not{E}_T$ at the LHC with the total luminosity $\mathcal{L} = 11.2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV, $\mathcal{L} = 40\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV, and $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14$ TeV. Additional kinematics cuts are $115 < M_{b\bar{b}} < 135$ GeV and $\not{E}_T > 100$ GeV. We have applied 10% systematic uncertainty, the b-tagging efficiency of $\epsilon_b = 67\%$, and the mistagging efficiency of $\epsilon_{\mathrm{mistag}} = 1.5\%$.

$\sqrt{s}$ at the LHC	$\ell b\bar{b} + \not{E}_T$ $(115 < M_{b\bar{b}} < 135$ GeV and $\not{E}_T > 100$ GeV$)$					
	7 TeV		8 TeV		14 TeV	
σ_{SM}	1.8 fb		2.2 fb		5.0 fb	
	σ_{signal}	$\frac{S}{\sqrt{B \oplus 0.1B}}$	σ_{signal}	$\frac{S}{\sqrt{B \oplus 0.1B}}$	σ_{signal}	$\frac{S}{\sqrt{B \oplus 0.1B}}$
$\kappa = 1$ $f = 500$ GeV	2.0 fb	3.5	2.9 fb	6.3	9.9 fb	13.7
$\kappa = 3$ $f = 500$ GeV	7.4 fb	12.9	11.1 fb	23.4	45.0 fb	62.0
$\kappa = 3$ $f = 700$ GeV	1.1 fb	1.9	1.8 fb	4.0	10.0 fb	13.7
$\kappa = 3$ $f = 1$ TeV	0.1 fb	0.2	0.2 fb	0.5	1.8 fb	2.5

and one neutrino. Naturally our signal has a harder $\not{E}_T$ distribution. We apply the following strong $\not{E}_T$ cut:

$$\not{E}_T > 100 \text{ GeV}. \tag{13}$$

Finally we apply b-tagging for both b quarks with the following efficiency [23]:

$$\epsilon_b = 67\%, \quad \epsilon_{\mathrm{mistag}} = 1.5\%. \tag{14}$$

In Table I, we summarize the signal and SM background cross sections, and the significance for $pp \to \ell b\bar{b} + \not{E}_T$ at the LHC with the total luminosity $\mathcal{L} = 11.2\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV, $\mathcal{L} = 40\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV, and $\mathcal{L} = 100\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 14$ TeV. For the model parameters, we consider four cases of $(f/\,\mathrm{TeV}, \kappa) = (0.5, 1), (0.5, 3), (0.7, 3), (1, 3)$. We have applied all of the above cuts. We also include 10% systematic uncertainty when computing the significance, which is inevitable with b jets.

8

First we compare two cases of $\kappa = 1$ and $\kappa = 3$ with the given $f = 500$ GeV. A larger κ value, which implies heavier T-odd quarks and smaller destructive interference between s-channel and $t(u)$-channel diagrams, leads to more signal events: the cross section of the $\kappa = 3$ case is bigger than that of the $\kappa = 1$ case by a factor of $3.7 \sim 4.5$. For $f = 500$ GeV even with small κ, the LHC has great potential of discovering $Z_H W_H$ production through the final state of $\ell b\bar{b} + \not{E}_T$, especially at $\sqrt{s} = 8, 14$ TeV. Increasing the value of f will lead to smaller cross sections. If $f = 700$ GeV and $\kappa = 3$, the discovery significance is high enough about 4 at $\sqrt{s} = 8$ TeV and above 13 at $\sqrt{s} = 14$ TeV. Although it is reduced considerably compared to the $f = 500$ GeV case, this case can be probed at the LHC. If $f = 1$ TeV, the decrease of the cross section is too severe. Even with a high luminosity $100\, \text{fb}^{-1}$ at $\sqrt{s} = 14$ TeV and even in the large κ case, the result does not yield high enough significance. The discovery significance of 5 at $\sqrt{s} = 14$ TeV is obtained if $f \lesssim 850$ GeV.

IV. CONCLUSIONS

Upon the discovery of a new boson with mass around 125 GeV, which shows incredible resemblance with the SM Higgs boson, we have studied the potential of the Higgs boson as a tagging particle in the LHT model. The $Z_H W_H$ production channel at the LHC has several merits for this purpose: (i) it has the largest cross section among heavy gauge boson production; (ii) both W_H and Z_H have practically one decay mode of $W_H \to W A_H$ and $Z_H \to H A_H$; (iii) the subsequent decays lead to a relatively clean final state of $\ell b\bar{b} + \not{E}_T$.

We have shown that the $\ell b\bar{b} + \not{E}_T$ final state from the $Z_H W_H$ production channel can yield high enough discovery significance for testing the model. With suggested kinematic cuts we are able to reduce the SM backgrounds to a manageable level, including the large QCD $Wb\bar{b}$, WZ, and WH production, as well as the reducible background of $t\bar{t}$ production. The signal significance at the LHC with $\sqrt{s} = 14$ TeV can be risen above 5 if $f \lesssim 850$ GeV and $\kappa = 3$.

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[1] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716** (2012) 1.

[2] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716** (2012) 30.

[3] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **710**, 49 (2012).

[4] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **710**, 26 (2012).

[5] T. Aaltonen *et al.* [CDF and D0 Collaborations], arXiv:1207.6436 [hep-ex].

[6] A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi and J. Quevillon, Phys. Lett. B **708**, 162 (2012); L. J. Hall, D. Pinner and J. T. Ruderman, JHEP **1204**, 131 (2012); S. Heinemeyer, O. Stal and G. Weiglein, Phys. Lett. B **710**, 201 (2012); J. L. Feng, K. T. Matchev and D. Sanford, Phys. Rev. D **85**, 075007 (2012); M. Carena, S. Gori, N. R. Shah and C. E. M. Wagner, JHEP **1203**, 014 (2012); P. Draper, P. Meade, M. Reece and D. Shih, Phys. Rev. D **85**, 095007 (2012); M. Kadastik, K. Kannike, A. Racioppi and M. Raidal, JHEP **1205**, 061 (2012); N. D. Christensen, T. Han and S. Su, Phys. Rev. D **85**, 115018 (2012); U. Ellwanger and C. Hugonie, Adv. High Energy Phys. **2012**, 625389 (2012).

[7] D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, JHEP **1210**, 196 (2012); A. Arhrib, R. Benbrik, M. Chabab, G. Moultaka and L. Rahili, JHEP **1204**, 136 (2012); J. Chang, K. Cheung, P. -Y. Tseng and T. -C. Yuan, JHEP **1212**, 058 (2012); R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stal, G. Weiglein and L. Zeune, Eur. Phys. J. C **72**, 2171 (2012); S. Dawson and E. Furlan, Phys. Rev. D **86**, 015021 (2012).

[8] N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513**, 232 (2001); N. Arkani-Hamed, A. G. Cohen and H. Georgi, Phys. Lett. B **513**, 232 (2001); N. Arkani-Hamed, A. G. Cohen, E. Katz and A. E. Nelson, JHEP **0207**, 034 (2002).

[9] I. Low, J. High Energy Energy Phys. 01 (2006) 135.

[10] H. -C. Cheng and I. Low, JHEP **0408**, 061 (2004); H. -C. Cheng and I. Low, JHEP **0309**, 051 (2003).

[11] C. Csaki, J. Hubisz, G. D. Kribs, P. Meade and J. Terning, Phys. Rev. D **67**, 115002 (2003); J. L. Hewett, F. J. Petriello and T. G. Rizzo, JHEP **0310**, 062 (2003); C. Csaki, J. Hubisz, G. D. Kribs, P. Meade and J. Terning, Phys. Rev. D **68**, 035009 (2003).

[12] A. Birkedal, A. Noble, M. Perelstein and A. Spray, Phys. Rev. D **74**, 035002 (2006); C. -S. Chen, K. Cheung and T. -C. Yuan, Phys. Lett. B **644**, 158 (2007); M. Perelstein and A. Spray, Phys. Rev. D **75**, 083519 (2007).

[13] J. Hubisz, P. Meade, Phys. Rev. **D71**, 035016 (2005).

[14] A. Belyaev, C. -R. Chen, K. Tobe, C. -P. Yuan, Phys. Rev. **D74**, 115020 (2006).

[15] Q. -H. Cao and C. -R. Chen, Phys. Rev. D **76**, 075007 (2007).

[16] A. Freitas and D. Wyler, JHEP **0611**, 061 (2006); S. Matsumoto, M. M. Nojiri and D. Nomura, Phys. Rev. D **75**, 055006 (2007); D. Choudhury and D. K. Ghosh, JHEP **0708**, 084 (2007); M. S. Carena, J. Hubisz, M. Perelstein and P. Verdier, Phys. Rev. D **75**, 091701 (2007).

[17] X. -F. Han, L. Wang, J. M. Yang and J. Zhu, arXiv:1301.0090 [hep-ph]; J. Reuter and M. Tonini, arXiv:1212.5930 [hep-ph]; C. -R. Chen, K. Tobe and C. -P. Yuan, Phys. Lett. B **640**, 263 (2006).

[18] J. Hubisz, P. Meade, A. Noble, M. Perelstein, JHEP **0601**, 135 (2006).

[19] I. Low, JHEP **0410**, 067 (2004).

[20] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **710**, 67 (2012).

[21] L. Wen, Z. Ren-You, G. Lei, M. Wen-Gan and C. Liang-Wen, arXiv:1302.0052 [hep-ph].

[22] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, JHEP **1106**, 128 (2011).

[23] [ATLAS Collaboration], ATLAS-CONF-2012-043; S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1211.4462 [hep-ex].